Theory & Observations of Beam-beam Interactions in the Tevatron

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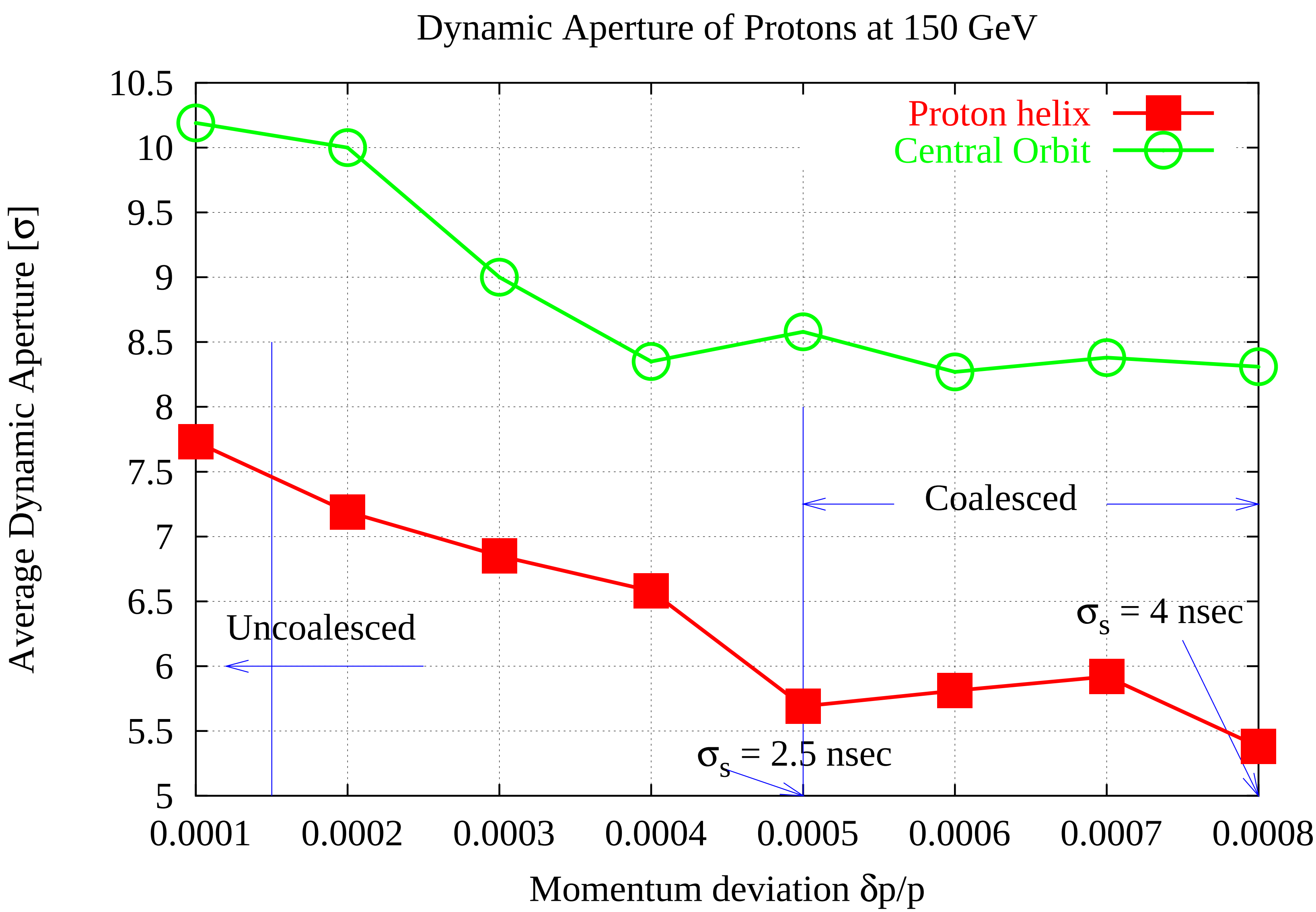
Tevatron Design Parameters

	Tevatron Run IIa
Luminosity [$\times 10^{31}$]	8.6
Bunch intensity [$\times 10^{11}$]	2.7/0.3
Normalized transverse emittance ($p/\bar{p}$) [95%, πmm-mrad]	20/15
RMS bunch length at top energy [cm]	37
RMS energy spread at top energy [$\times 10^{-4}$]	0.9
β^* [cm]	35
Beam-beam tune shift/IP [$p/\bar{p}$]	0.0014/0.01
Number of bunches	36
Total number of parasitics	72

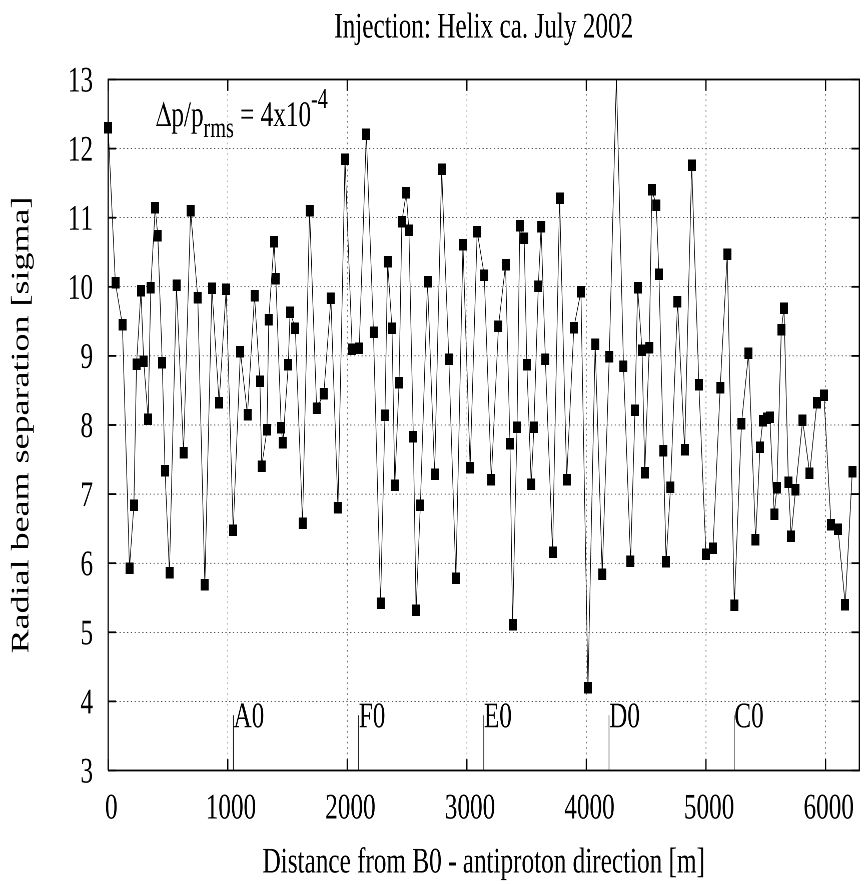
Beam Losses in the Tevatron

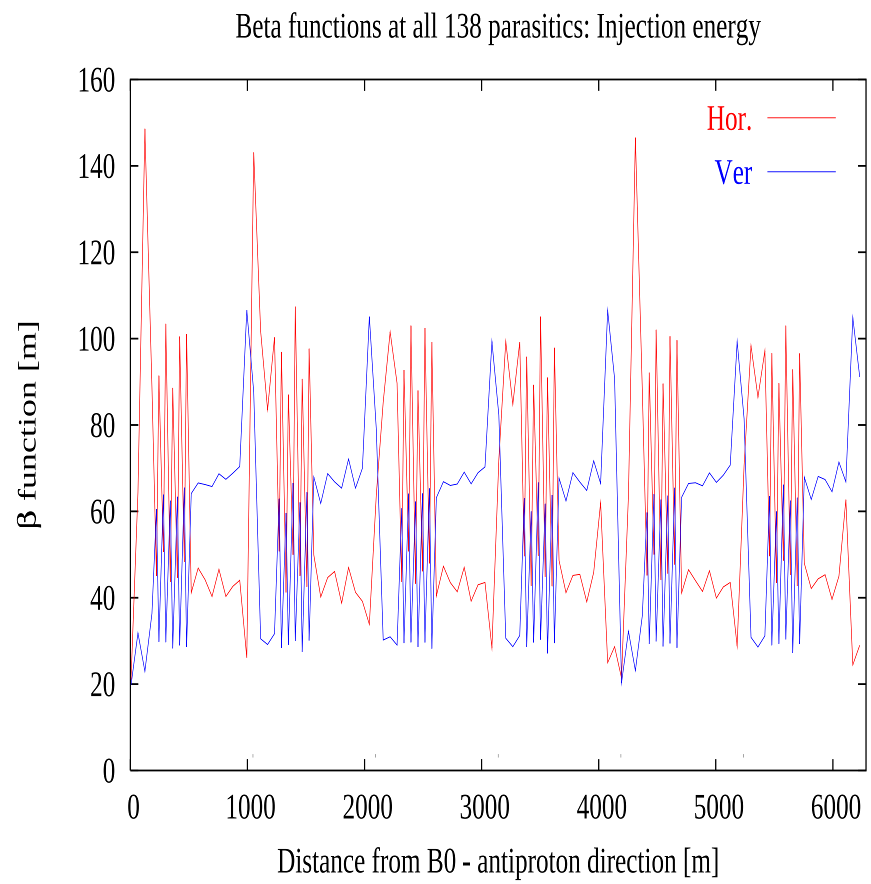
	03/02	10/02	01/03	03/03
Protons/bunch at low-beta	140e9	170e9	180e9	205e9
Anti-protons/bunch at low-beta	7.5e9	22e9	20e9	23e9
P-loss at 150 GeV	23%	14%	16%	**10%**
Anti-proton-loss at 150 GeV	20%	9%	4%	4%
P-loss on ramp	7%	6%	9%	5%
Anti-proton-loss on ramp	14%	8%	12%	**11%**
Anti-proton-loss in squeeze	25%	5%	3%	2%

Dynamic aperture of protons at 150 GeV



Beam Separations at Injection





Beam-beam parameters vs Helix Angle

For round beams and large separations ($d \gg 1$), small amplitude parameters

$$\Delta\nu_x(0,0) \;\propto\; \frac{\cos 2\theta}{d^2}$$

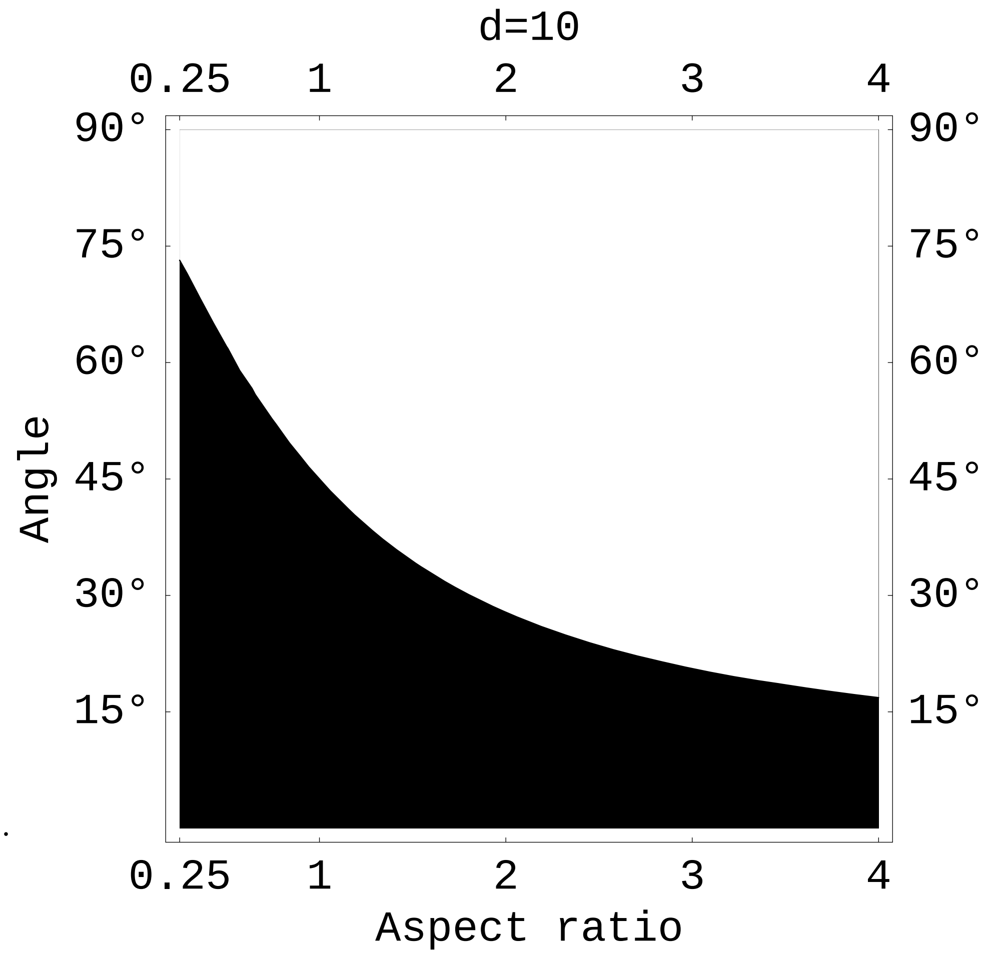
$$\Delta\nu'_x(0,0) \;\propto\; \frac{\cos\theta(2\cos 2\theta - 1)}{d^3}\eta_x$$

$$\Delta\nu_{min}(0,0) \;\propto\; \frac{\sin 2\theta}{d^2}$$

$\Rightarrow$

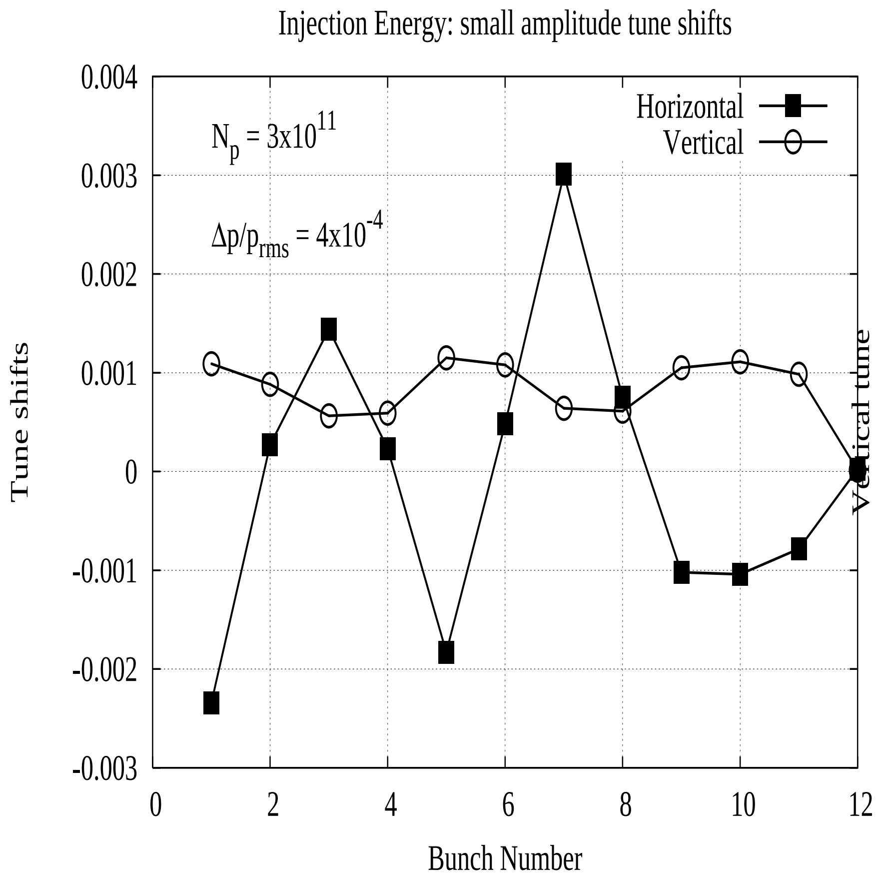
$\Delta\nu = 0$ along the diagonal
$\Delta\nu' = 0$ along 30° or the vertical axis.
$\Delta\nu_{min} = 0$ along the horizontal or vertical axis.

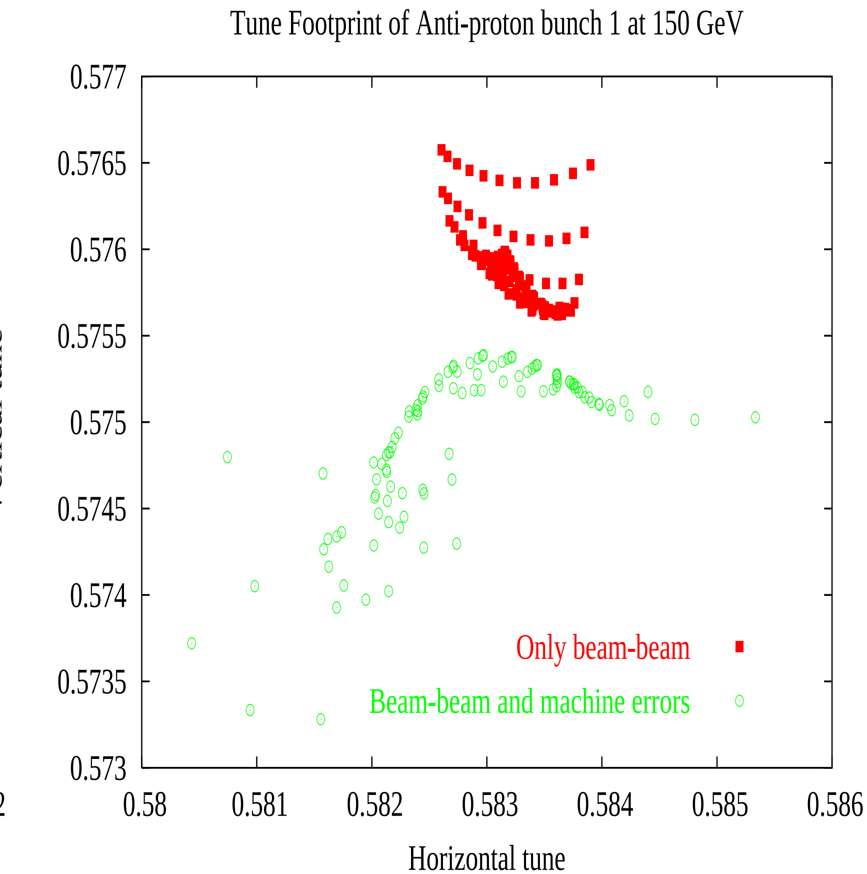
For arbitrary aspect ratio $\Rightarrow$



The tune shift is negative in the dark region and vanishes along the border.

Small amplitude tune shifts & Tune footprints: Injection

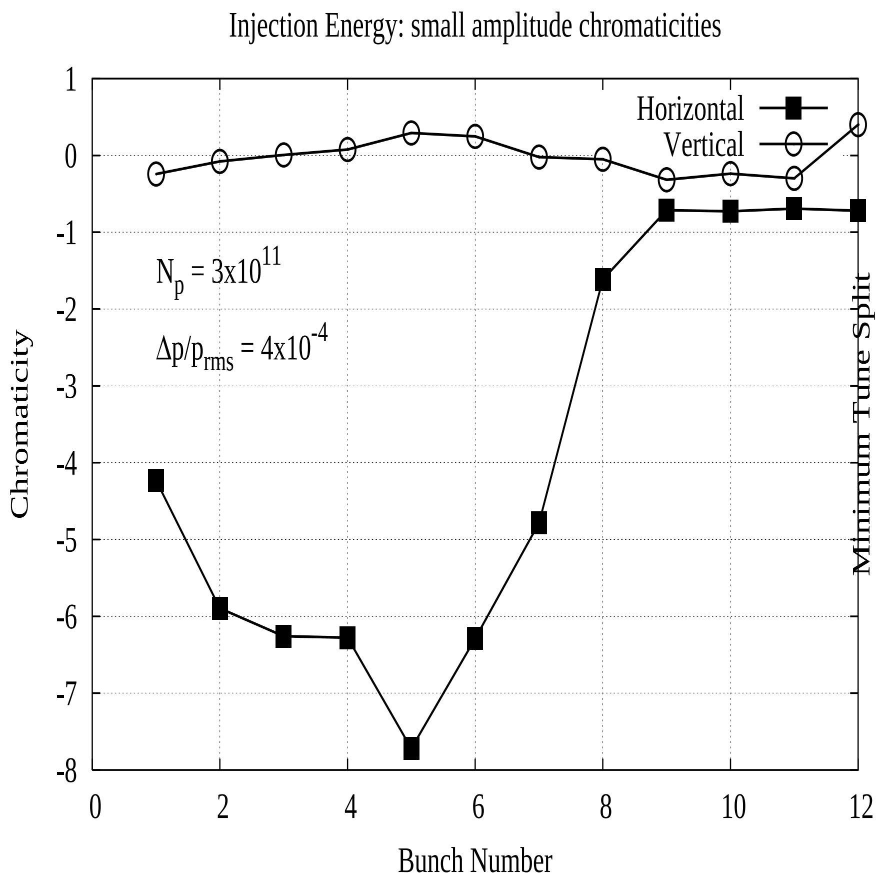


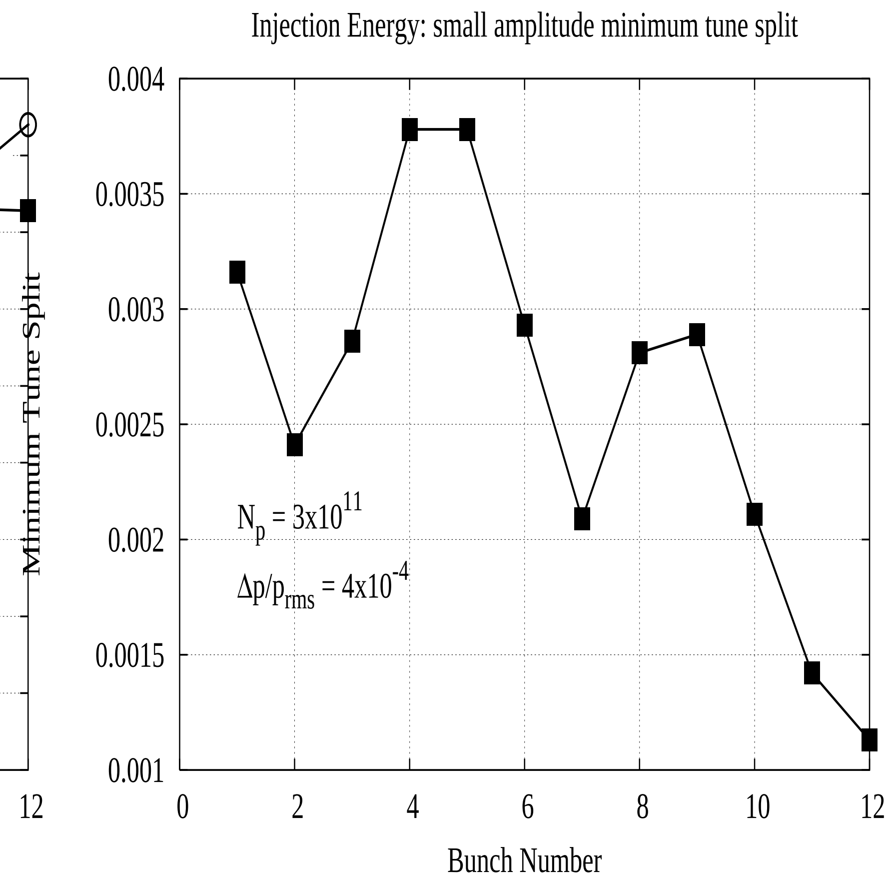


Bunch to bunch tune spread $\Delta\nu_x \sim 0.005$.

Changes are small at the end of a train: A9-A12

Small amplitude chromaticities and coupling: Injection

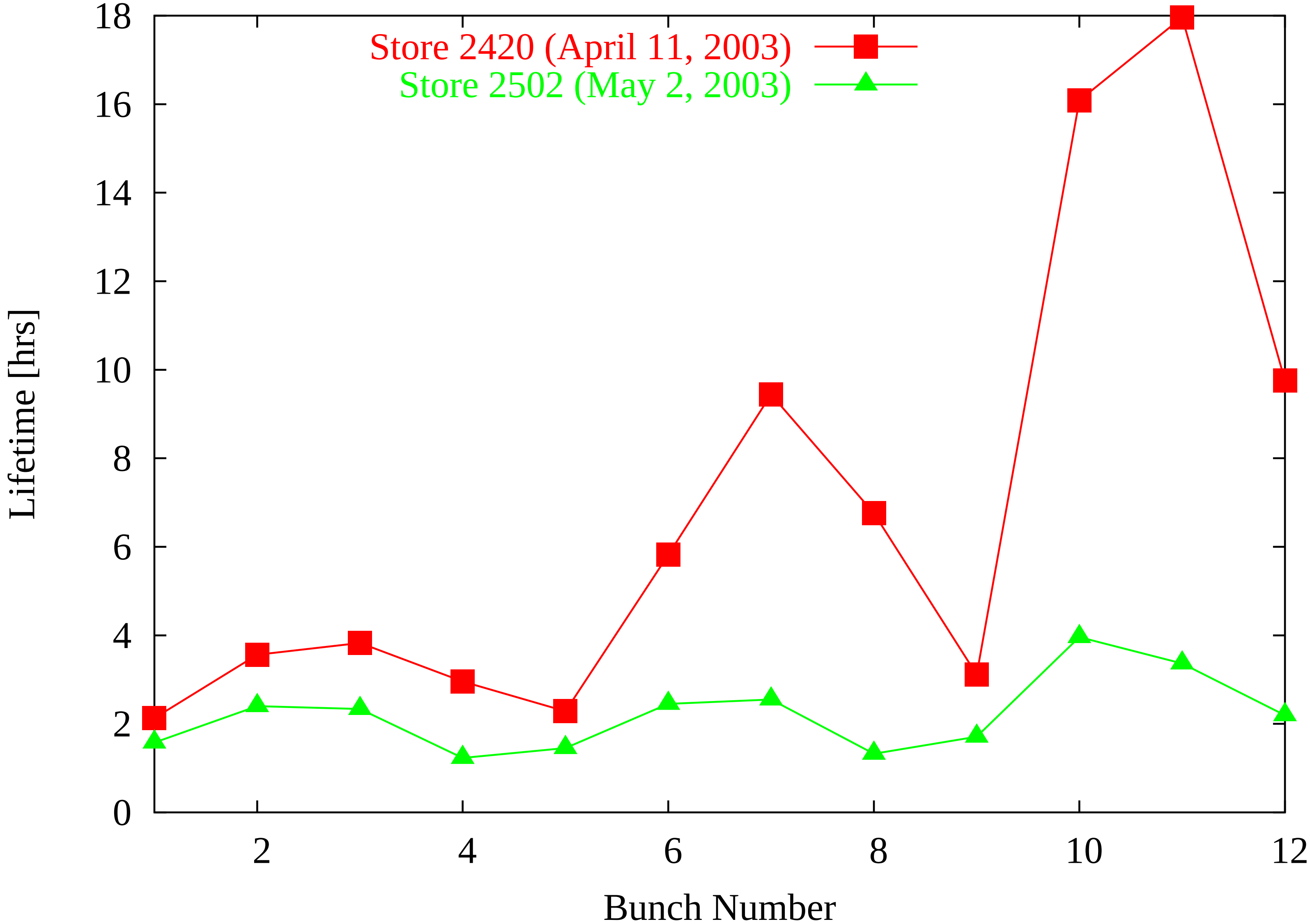




Beam-beam chromaticity → some bunches more susceptible to synchro-betatron resonances, instabilities.

Changes are small towards the end of a train.

Anti-proton lifetimes at Injection: Stores 2420, 2502



Linear to Square Root Lifetime

Diffusion Equation (1D)

$$\frac{\partial f}{\partial \tau} = \frac{\partial}{\partial Z}[Z\frac{\partial f}{\partial Z}]$$

$\tau \equiv (\frac{d\langle J\rangle}{dt}/J_a)t$, $Z \equiv J/J_a$.

Solution

$$N(\tau) = 2\sum_n \frac{c_n}{\lambda_n} J_1(\lambda_n) e^{-\lambda_n^2 \tau/4}$$

$$c_n = \frac{1}{J_1(\lambda_n)^2}\int_0^1 f_0(Z) J_0(\lambda_n \sqrt{Z}) dZ$$

If transverse ($\epsilon_\perp = 20\pi$ mm-mrad)

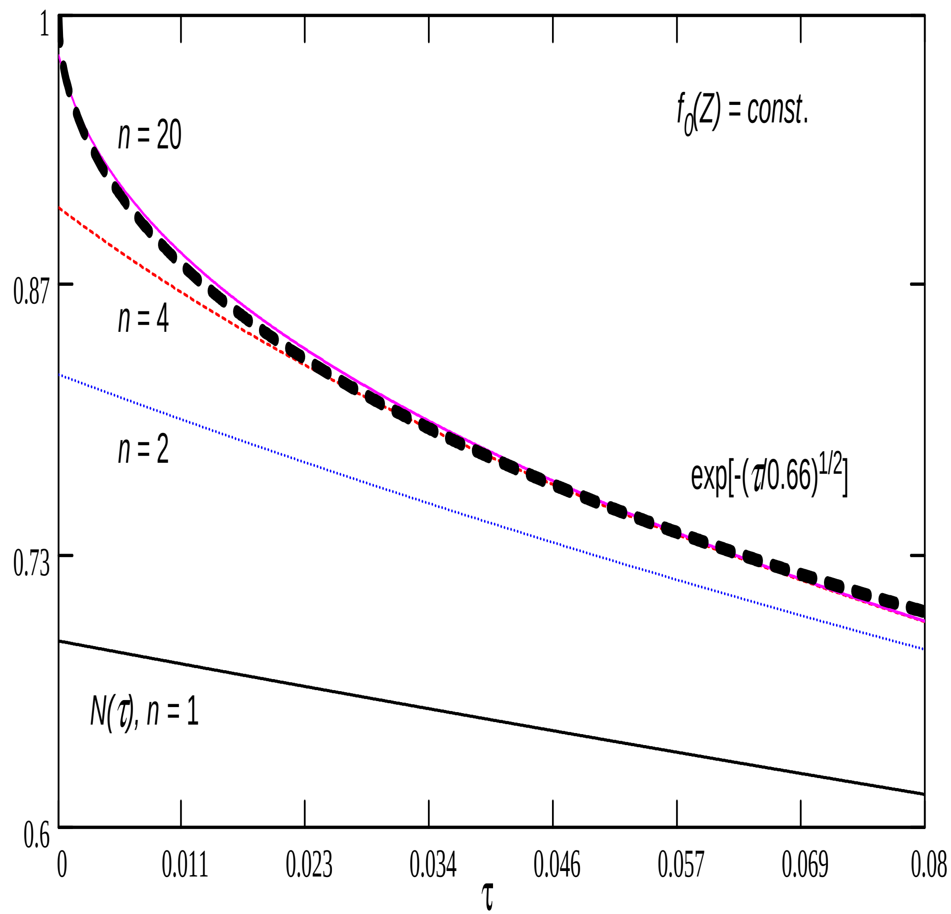
$$\Rightarrow \dot{\epsilon} \approx 16\pi \;\; \mathrm{mm-mrad/hr}$$

Very large.

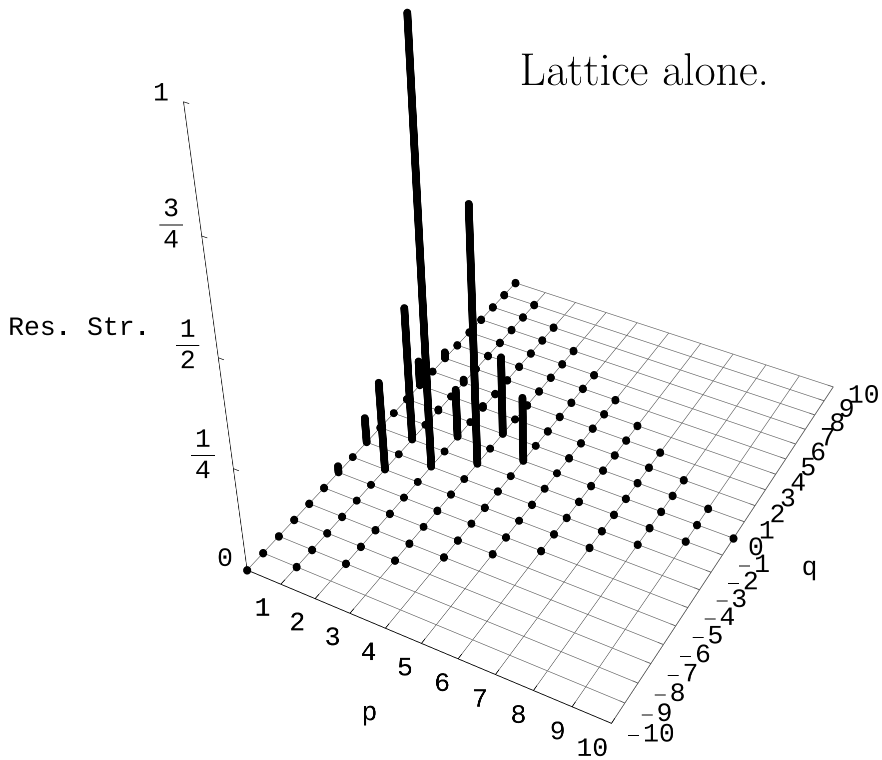
If longitudinal (4 eV-sec bucket)

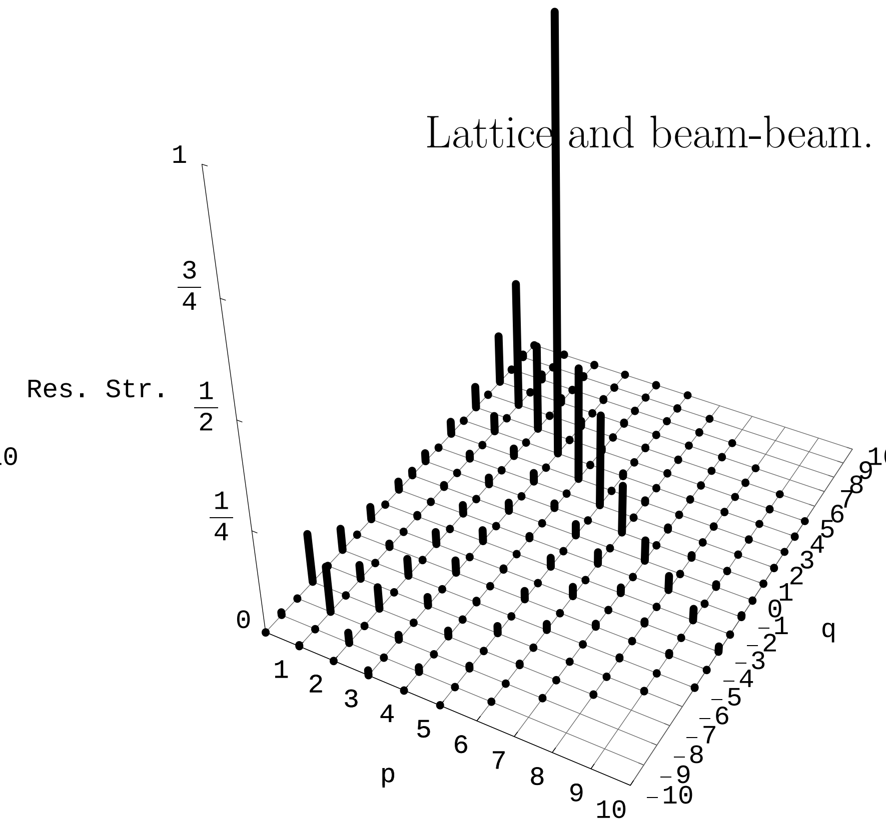
$$\Rightarrow \dot{\epsilon}_s \approx 1/3 \;\; \mathrm{eV-sec/hr}$$

Reasonable



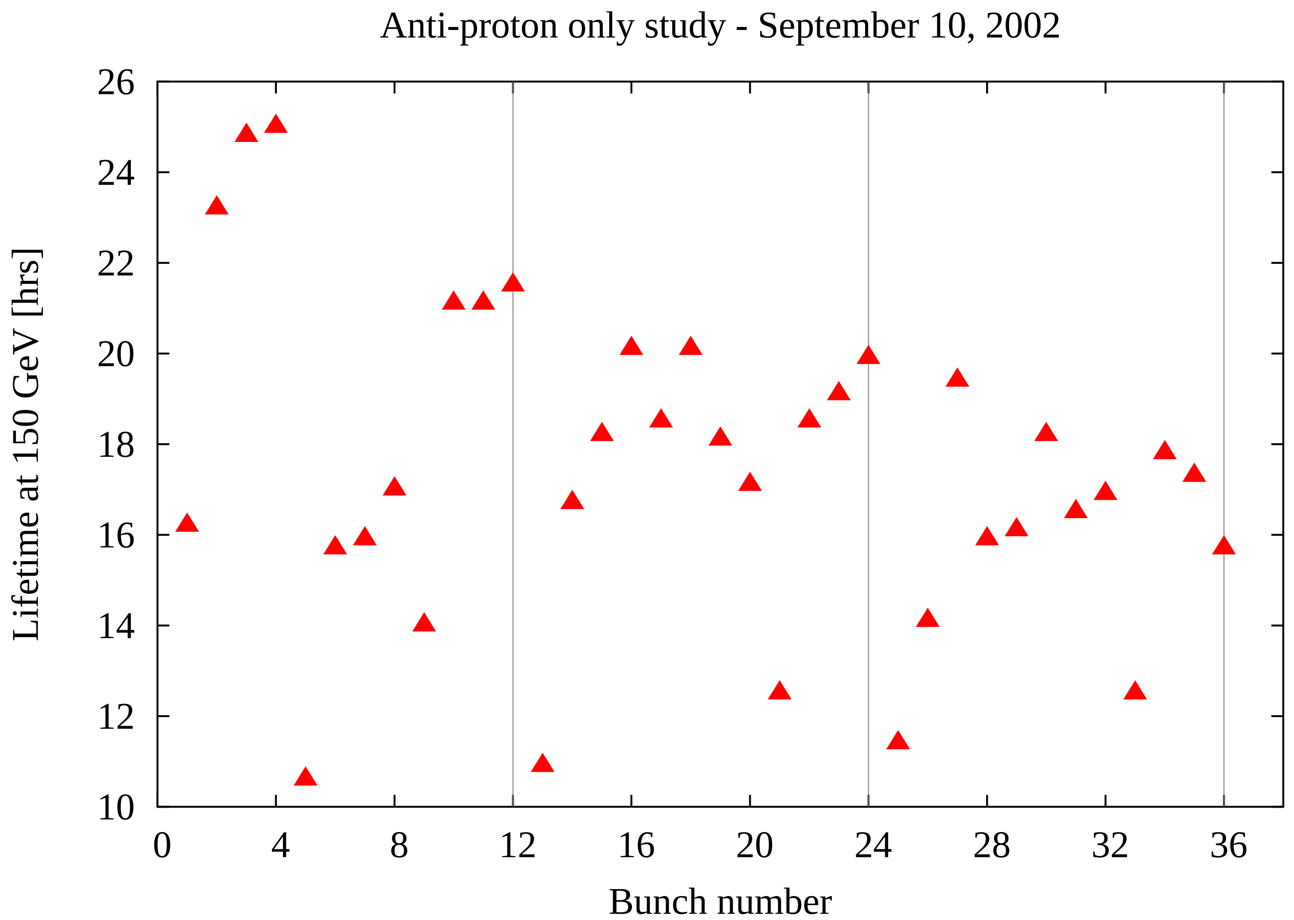
Resonances at Injection





	Resonances (p, q) at 2σ	
	Largest	Others
Lattice driven	(2, -2)	(3,-1), (1,-1), (1,-3), (3,1), (4, 0)
Lattice and beam-beam driven	(3, 4)	(1, 6), (4, 3), (5, 2), (2, 5), (0, 7)

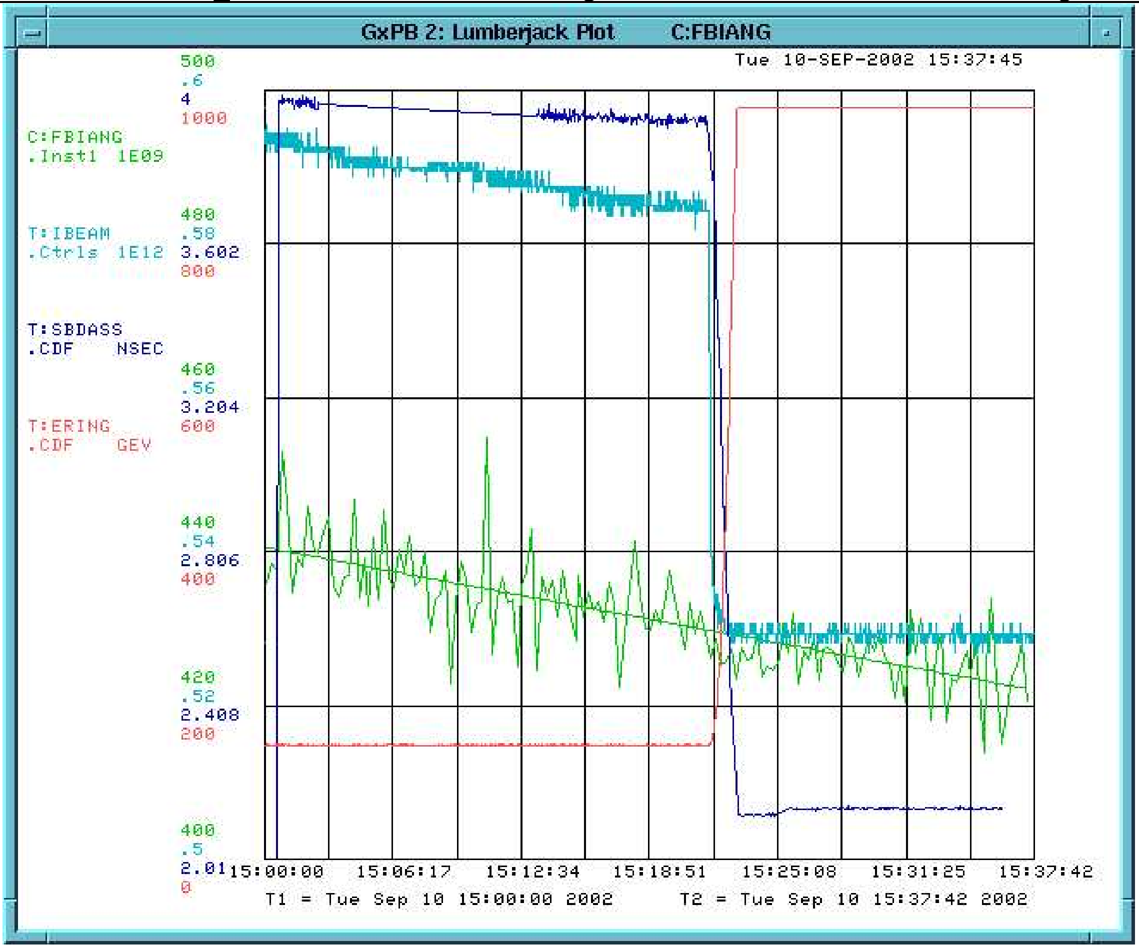
Anti-protons only - Beam Study



In this study, τ was well anti-correlated with the vertical emittance.

In typical stores, $1 \leq \tau(\bar{p}) \leq 10$ hours.

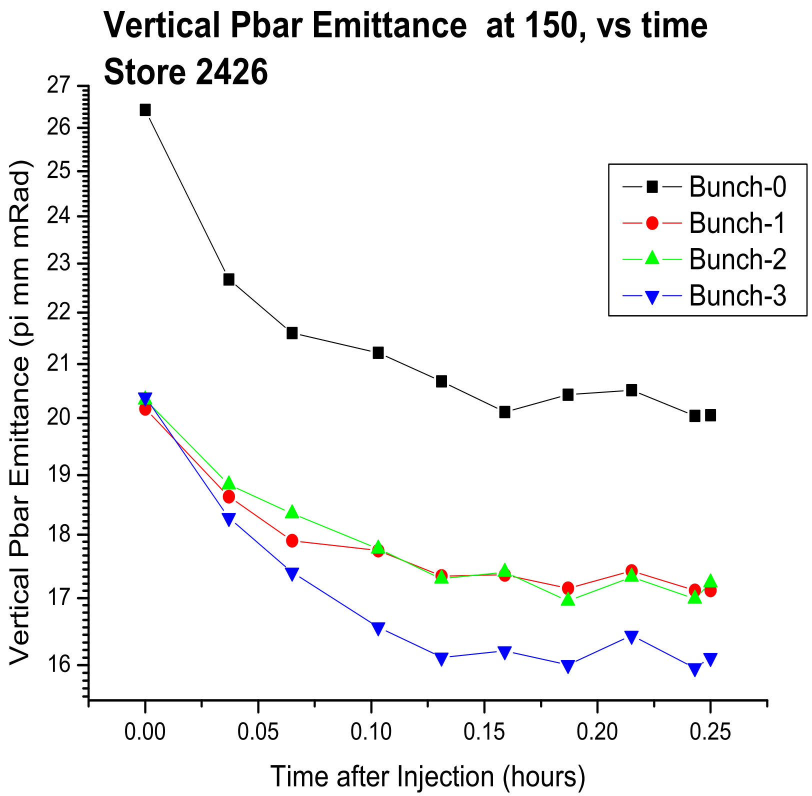
Anti-protons only - Beam Study

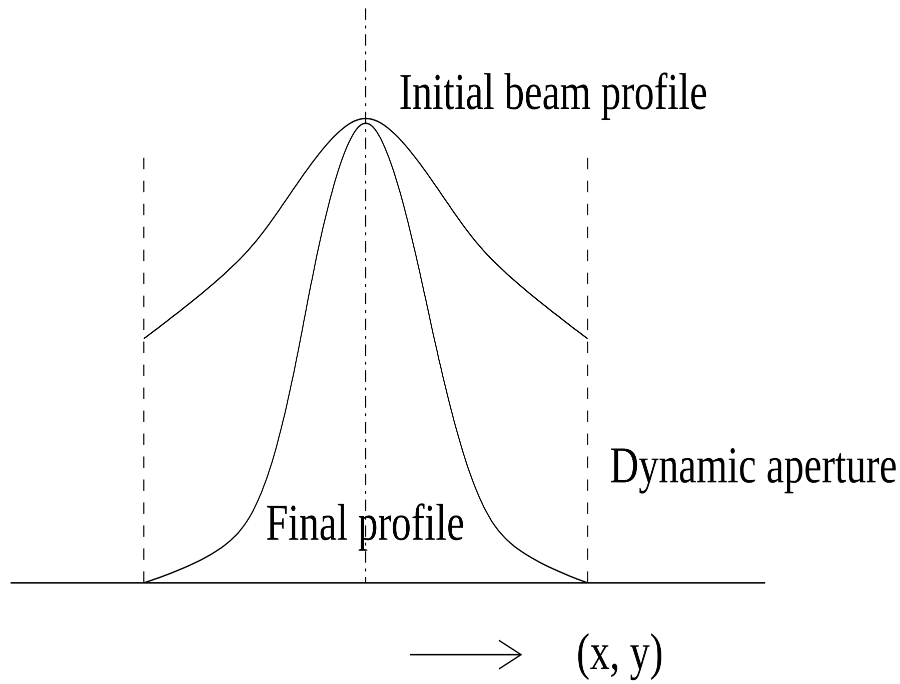


Loss of anti-protons during the ramp was very small $\sim 2\%$.

In typical stores, anti-proton losses during the ramp are $\sim 10\%$.

Anti-proton dynamic aperture at 150 GeV





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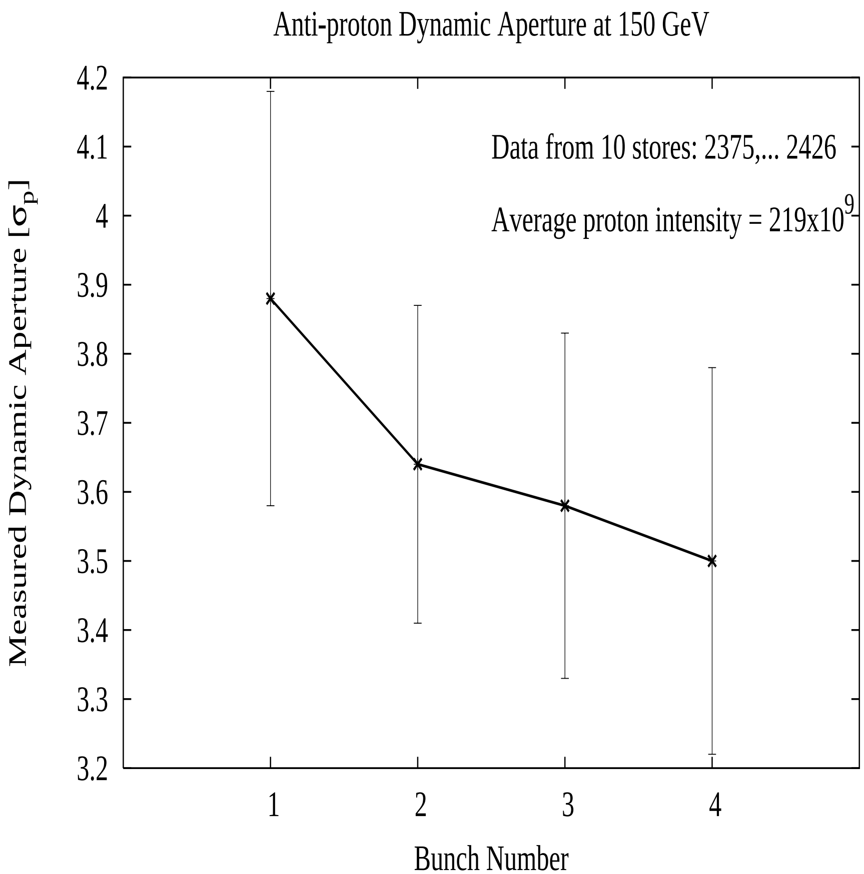
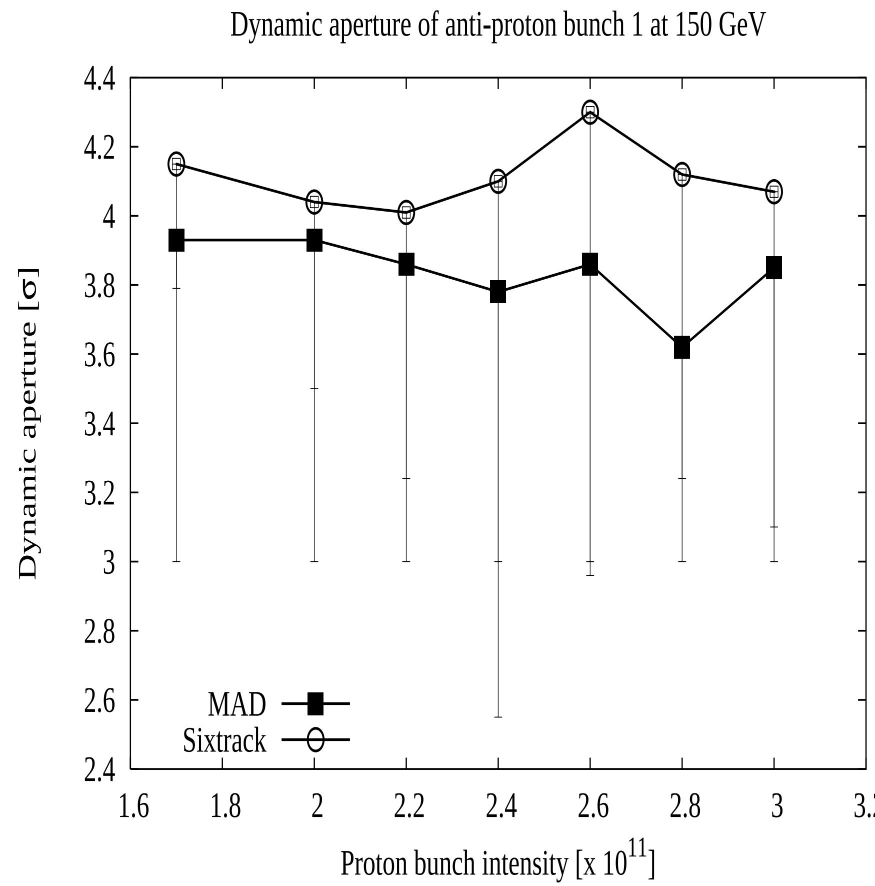
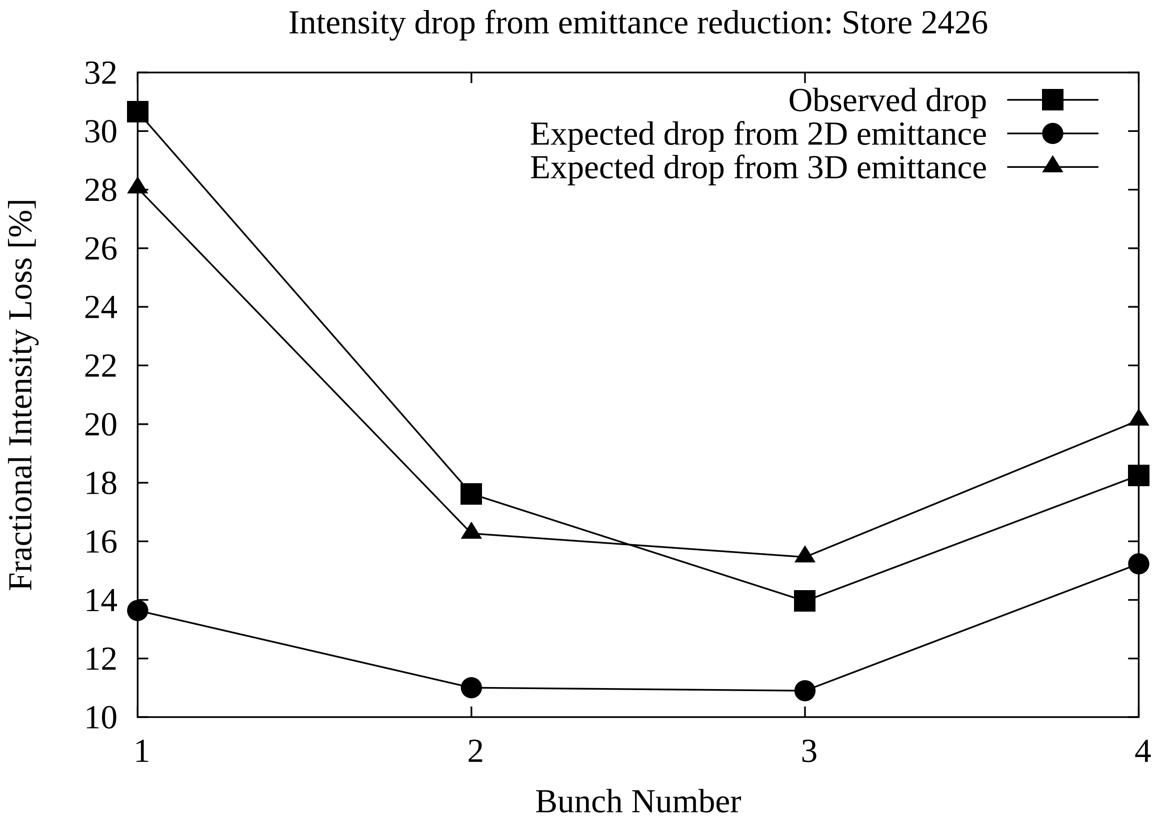


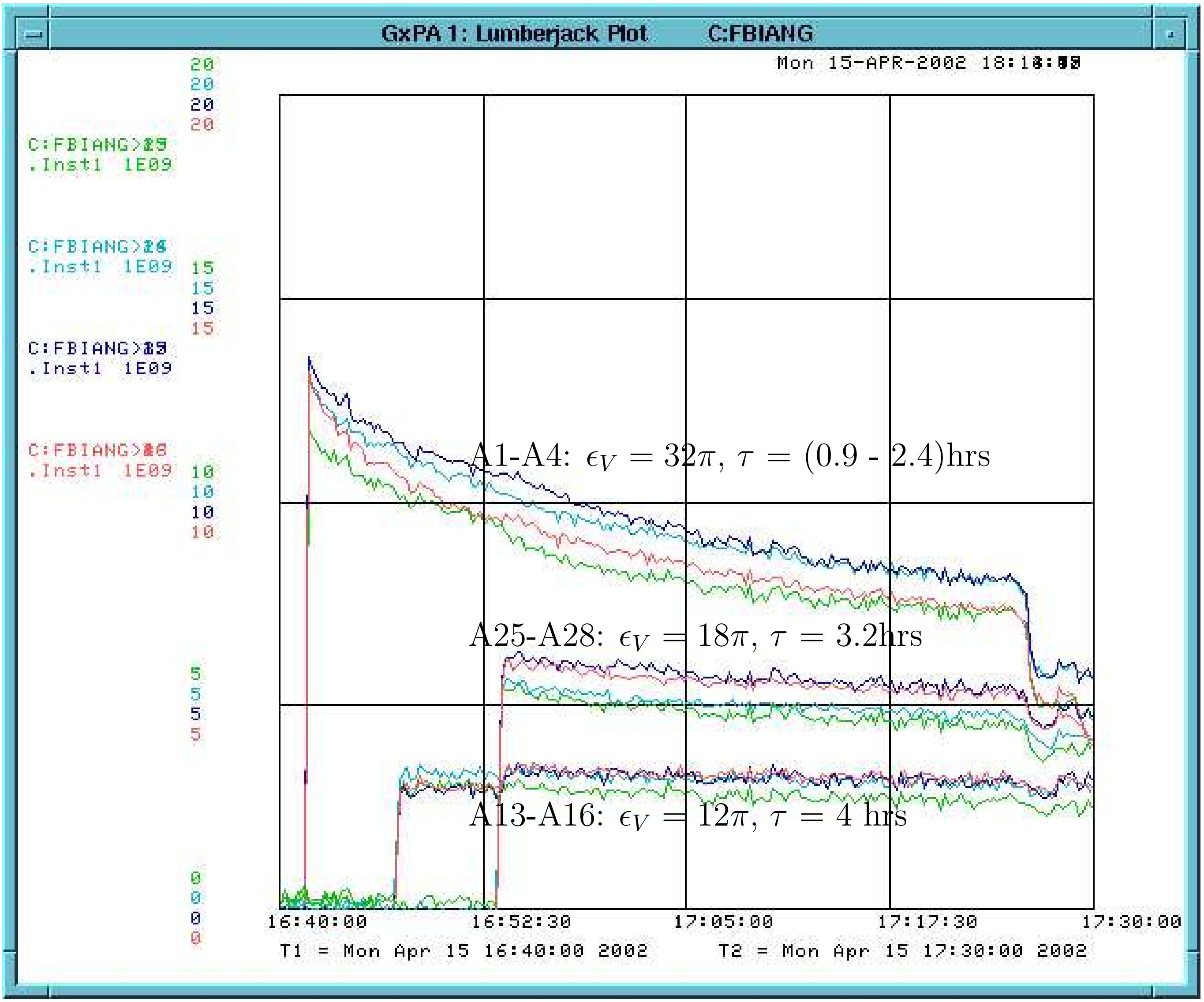


Expected and Measured Intensity Drop: Store 2426

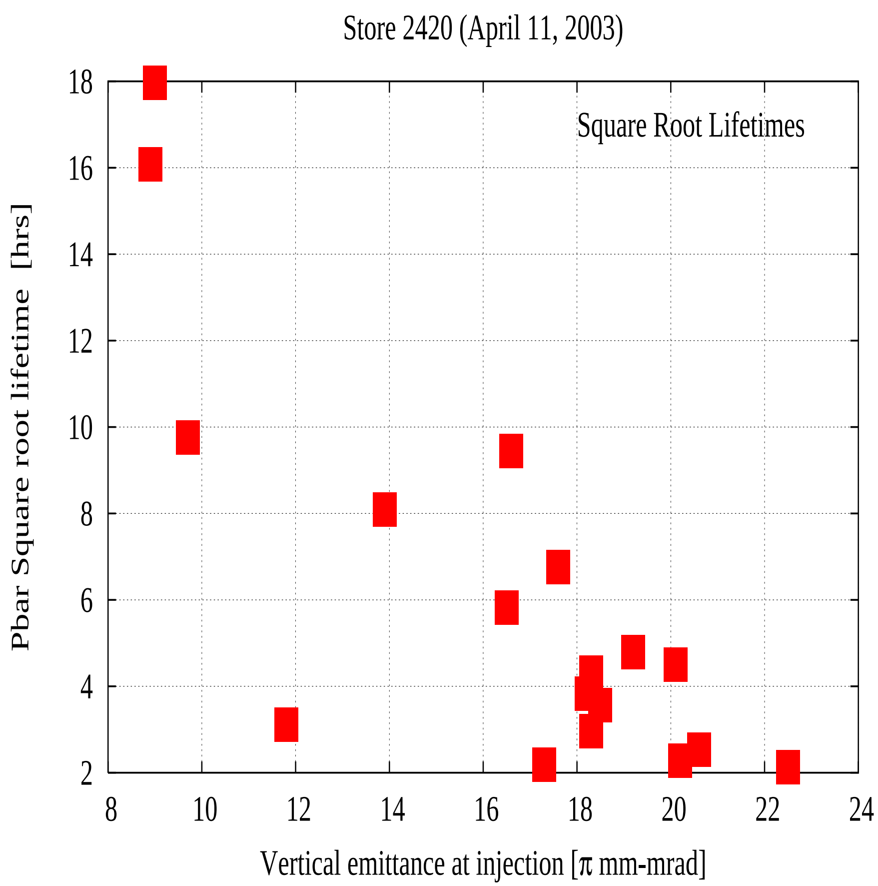


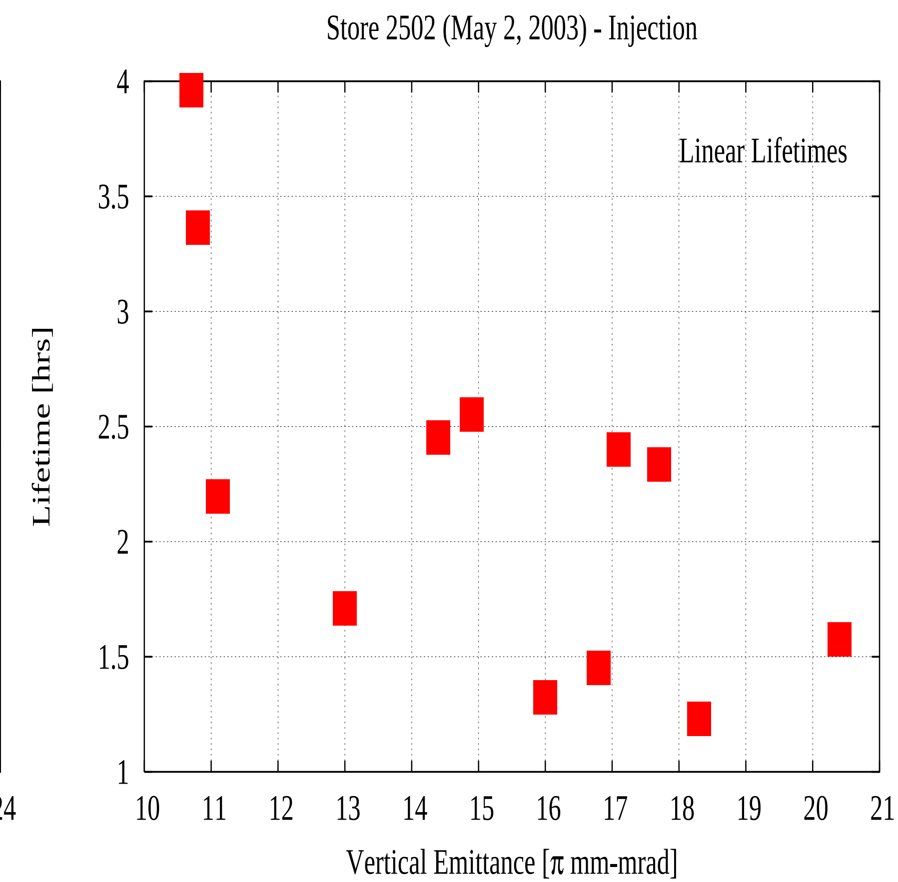
- The expected drop in intensity was calculated from the final bunch area (2D and 3D). The bunches are assumed to completely fill their dynamic aperture. The expected 3D loss and measured loss agree to within 2%.
- The largest difference in 2D and 3D areas was for bunch 1. This bunch had the greatest reduction in longitudinal emittance.
- This store occurred before the vertical dampers were restored. Since then, we have not seen this significant emittance shaving at injection.

Anti-proton lifetime at 150 GeV



Anti-proton lifetime vs Vert. Emittance at 150 GeV





Lifetime Simulations at 150 GeV

Parallel codes have been developed that run at NERSC

- A. Kabel(SLAC): Code `PlibB`

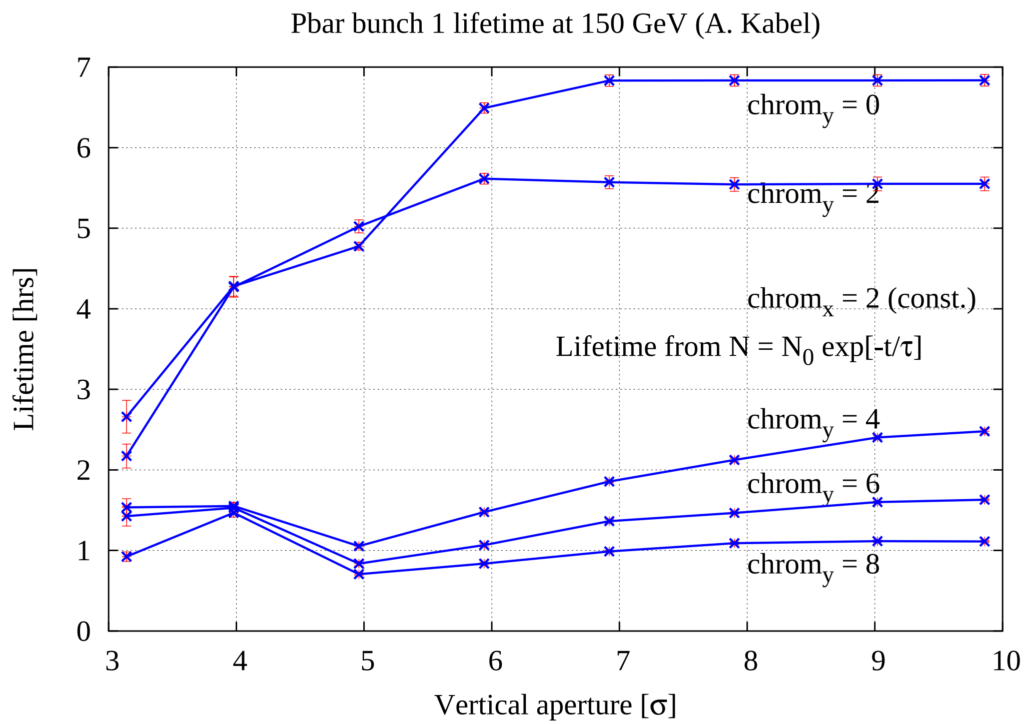
  Fast evaluation of complex error function

- J.Qiang(LBNL): Code `Beambeam3D`

  Uses a shifted Green's function approach

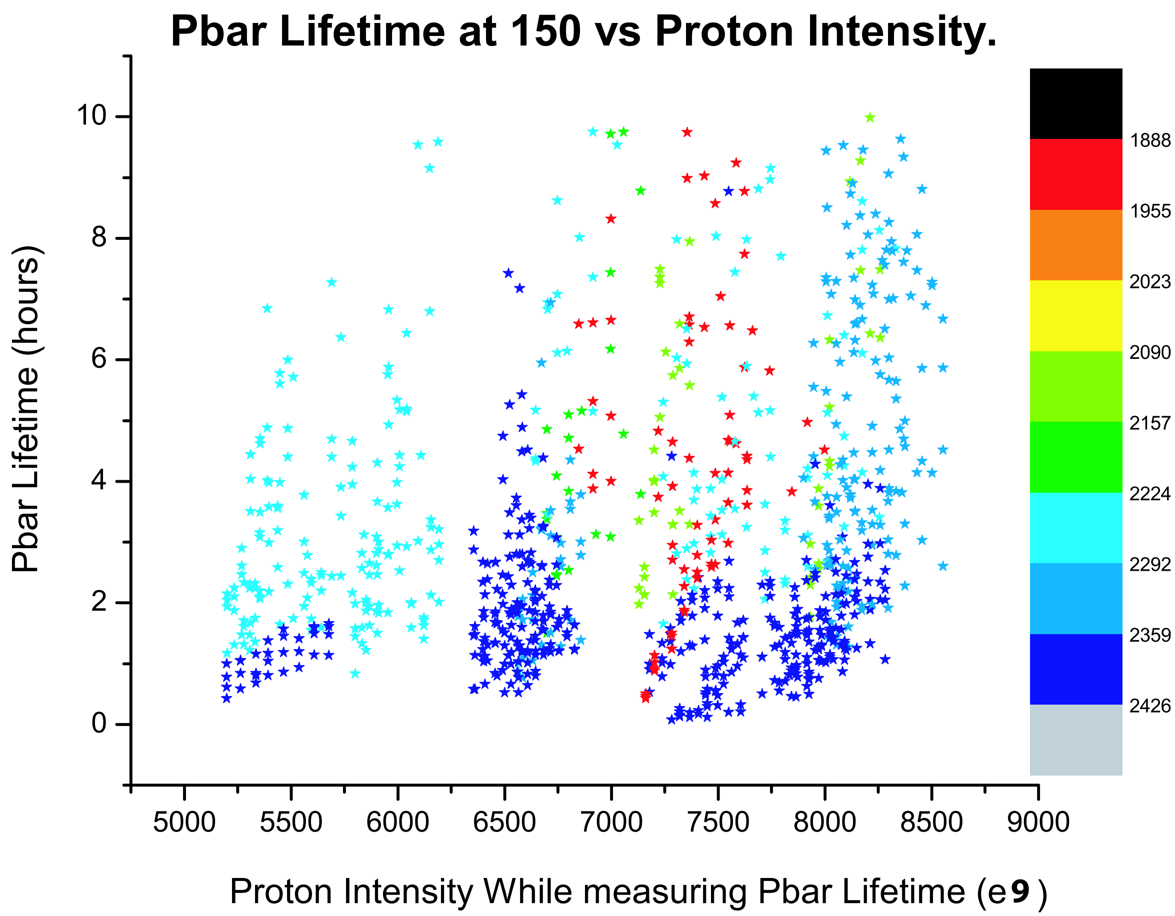
Both codes include the long-range interactions and transverse noise.

At small apertures, both predict lifetimes close to the observed lifetimes.



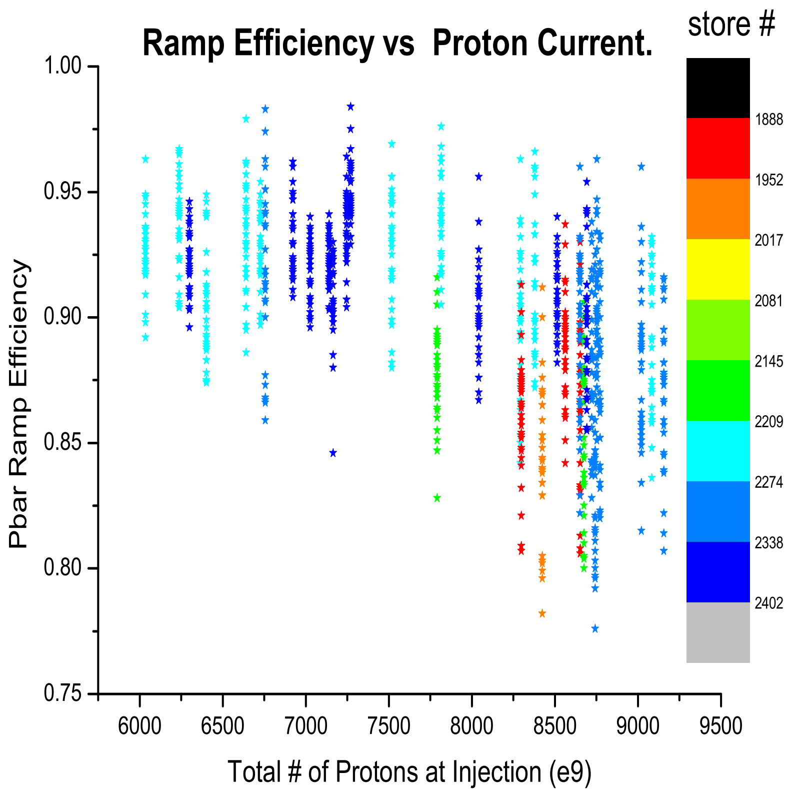
This predicts a qualitative increase in lifetime when the vertical chromaticity is dropped below 4 units.

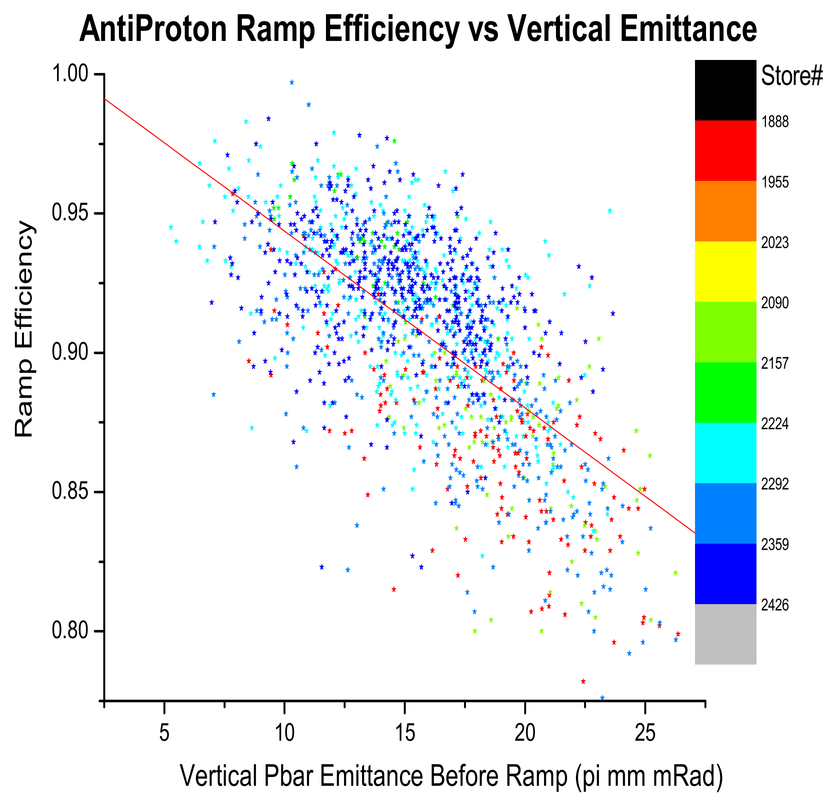
Anti-proton lifetime at Injection - Several Stores



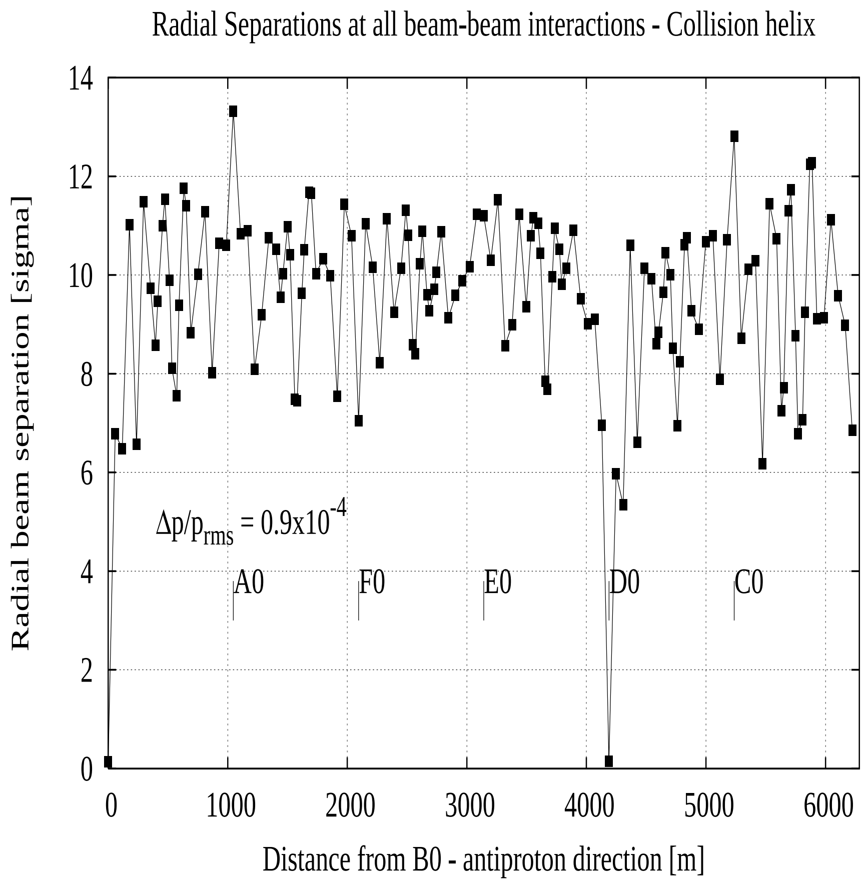
Dependence of anti-proton lifetime on proton intensities is low so far.

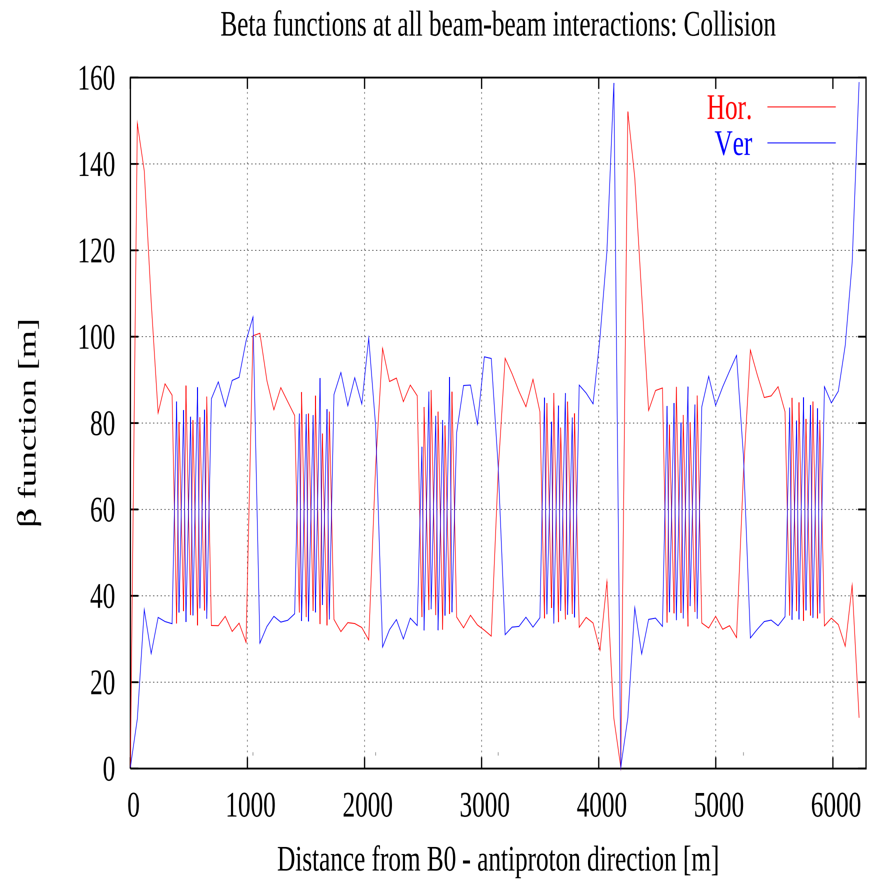
Anti-proton ramp efficiency in stores



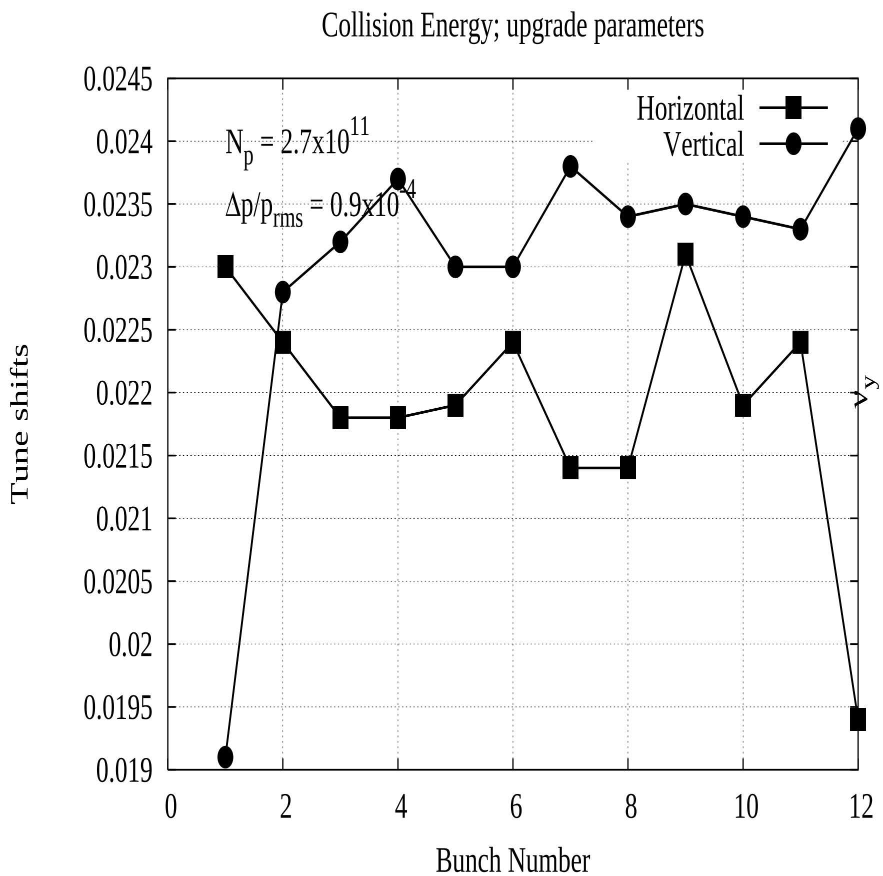


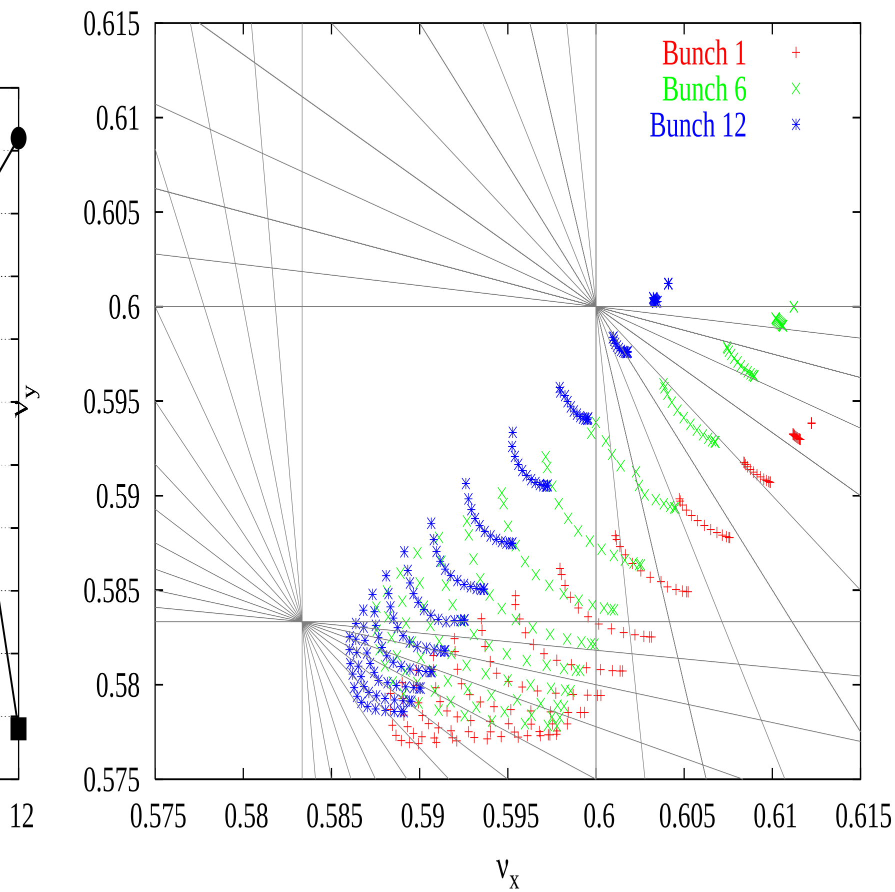
Beam Separations at 980 GeV





Small amplitude tune shifts & Tune footprints: Collision

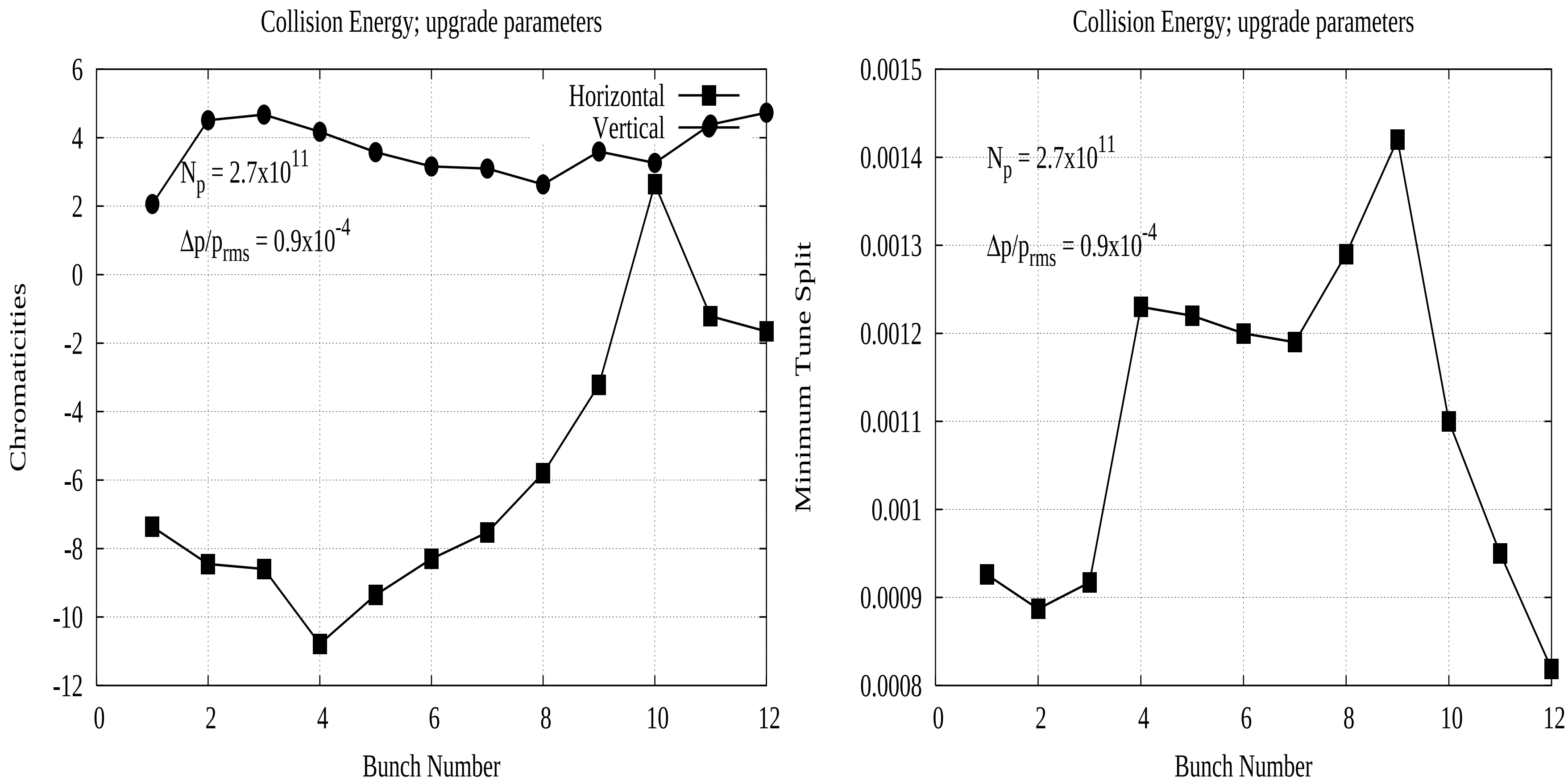




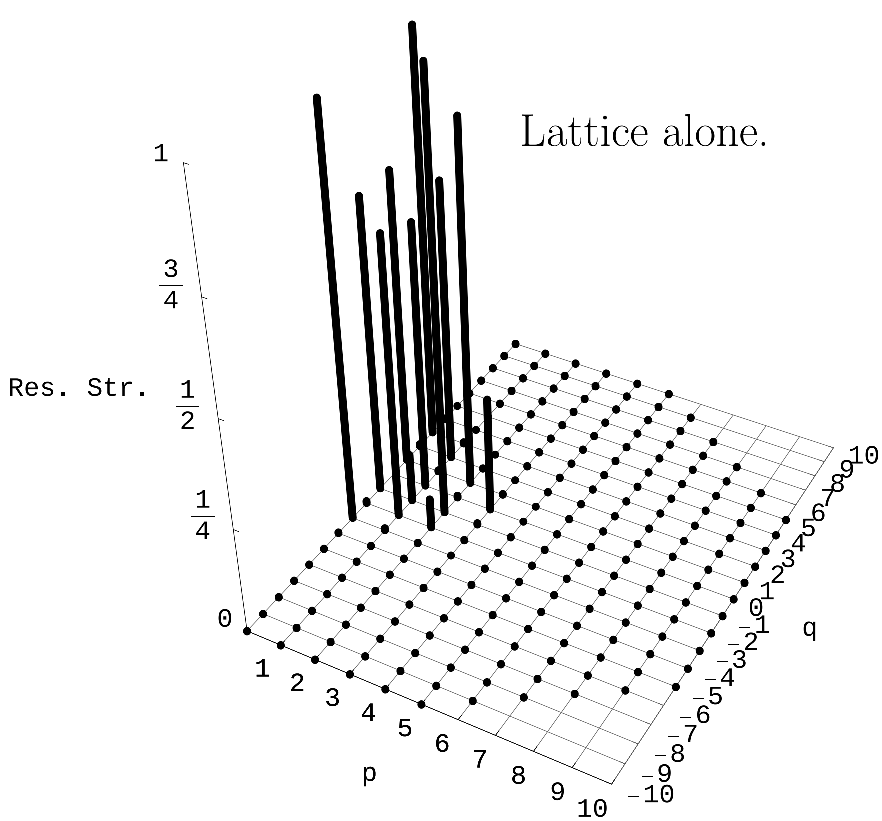
Bunch 1 has lower ν_x, bunch 12 has lower ν_y.

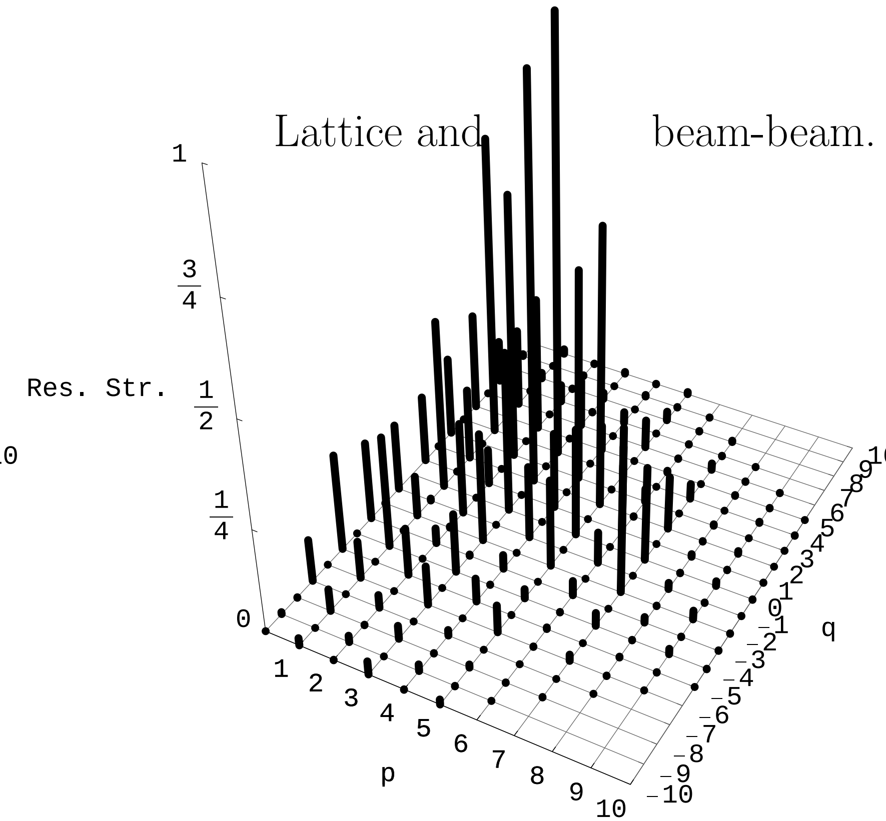
Spread between bunches 2-11: $\Delta\nu_x \sim 0.0015$, $\Delta\nu_y \sim 0.001$.

Small amplitude chromaticities and coupling: Collision



Resonances at Collision





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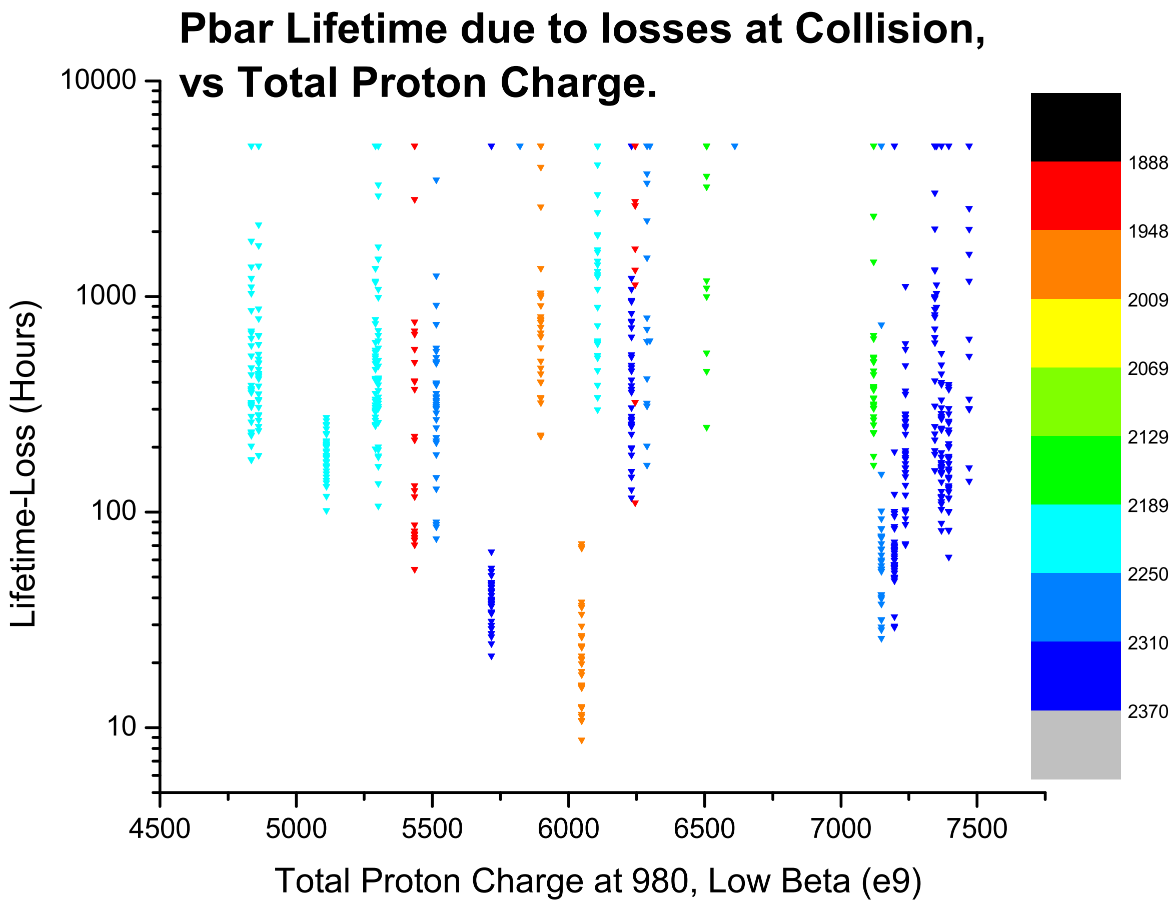
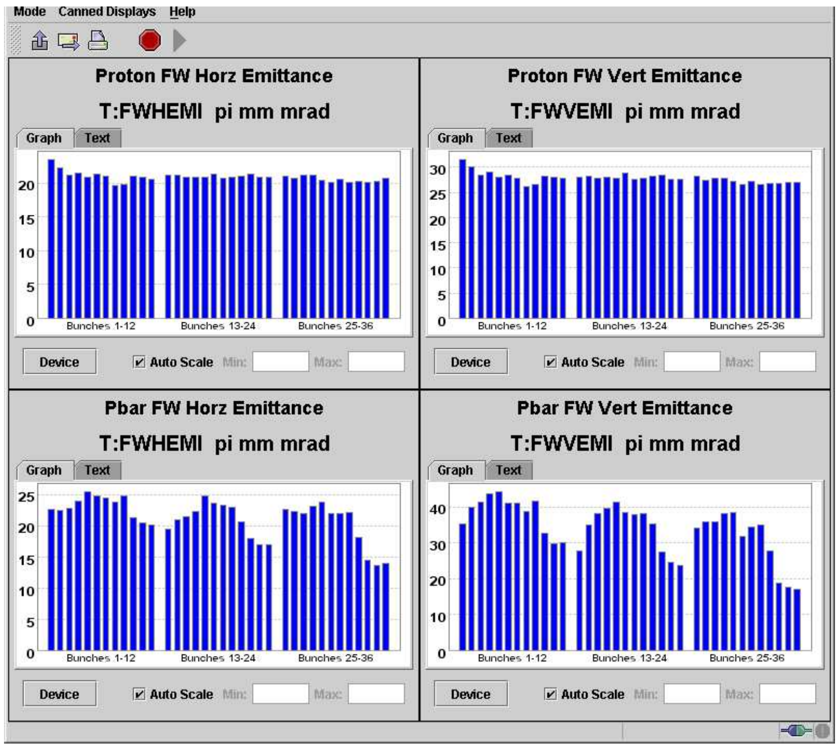
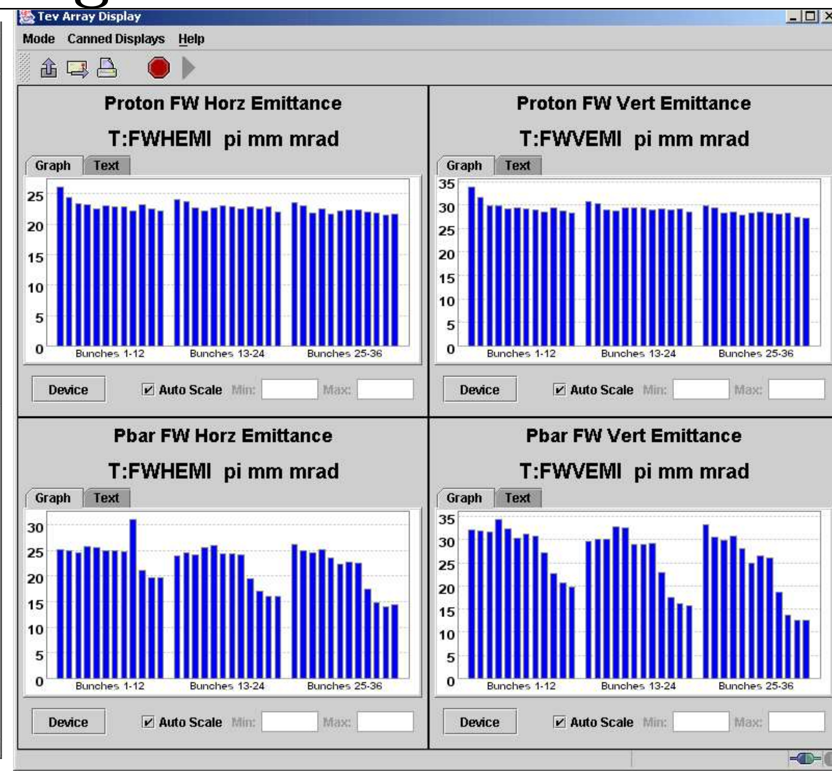


Pbar Lifetime due to losses at Collision,
vs Total Proton Charge.
Lifetime-Loss (Hours)
10000
1000
100
10
4500
5000
5500
6000
6500
7000
7500
Total Proton Charge at 980, Low Beta (e9)
1888
1948
2009
2069
2129
2189
2250
2310
2370

Anti-proton emittance growth at Collision

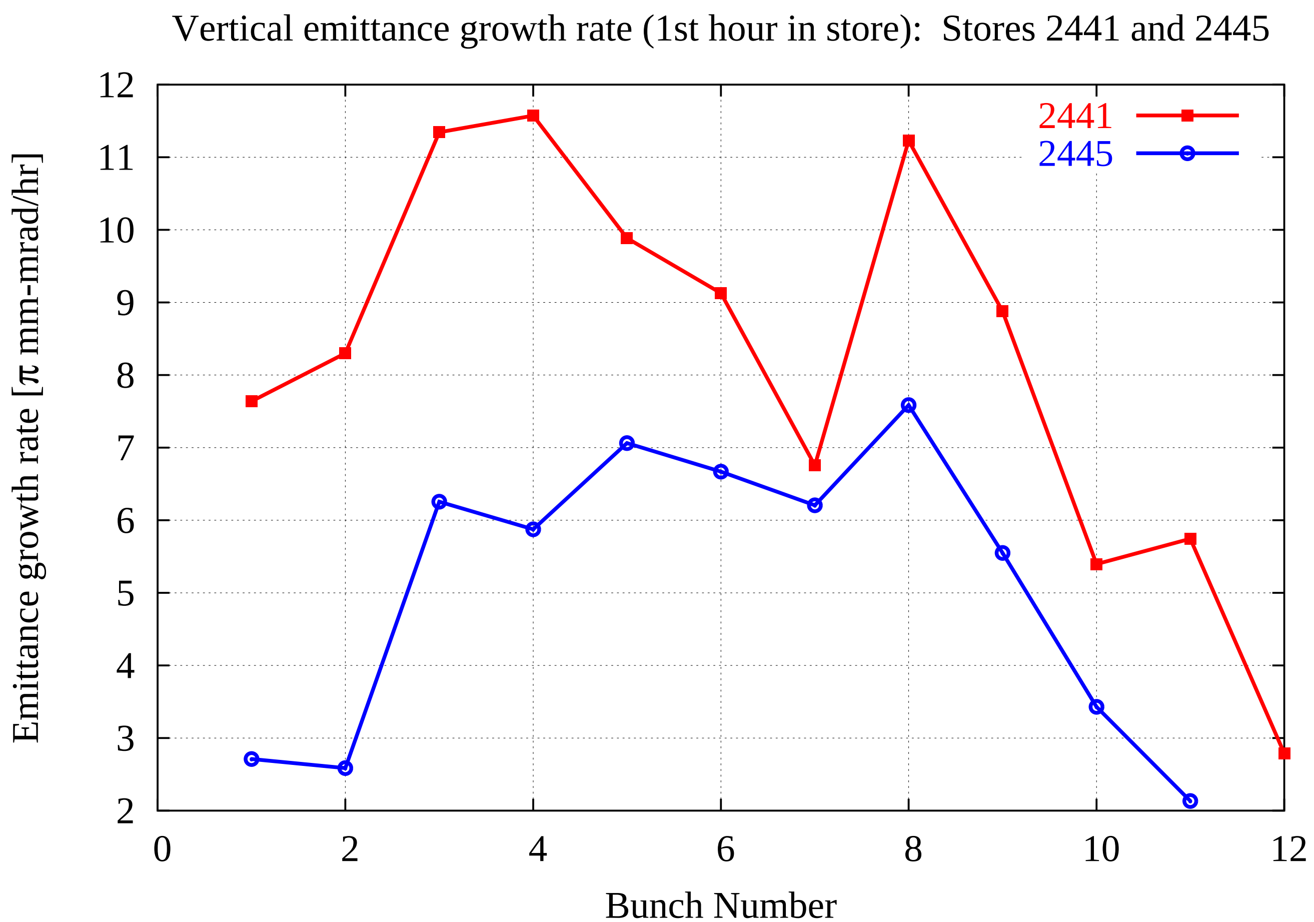


Start of Store 2441.



Start of Store 2445: $\Delta\nu_y$ =- 0.001.

Anti-proton emittance growth at Collision



Vertical emittance growth rates in the two stores.

Losses vs Helix Size

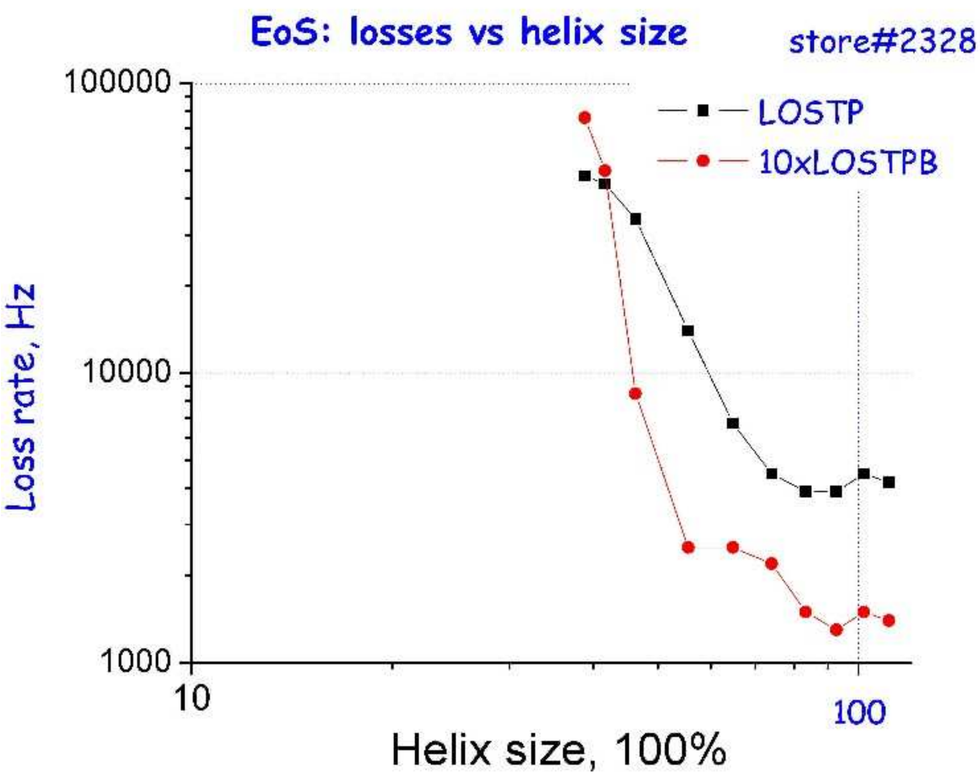


Figure 1: Losses (at end of store) vs helix size.

Losses were observed at the end of a store by changing the helix size in both planes. Increasing the helix size to 10%

$$\begin{aligned} \tau(p) &= 86\text{hrs} \to 68\text{hrs} \\ \tau(\bar{p}) &= 43\text{hrs} \to 33\text{hrs} \end{aligned}$$

Decreasing the helix size to 80% of original

$$\begin{aligned} \tau(p) &\to 141\text{hrs} \\ \tau(\bar{p}) &\to 67\text{hrs} \end{aligned}$$

- Emittances did not change much at the end $\Rightarrow$ tails were lost
- Tunes decreased < 0.002 down to 65% of original helix.

  Sharp losses at the end were likely due to (7th, 12th) order resonances.

Status of Beam-beam effects

- **Injection**
  - Limit anti-proton lifetimes to under 10 hrs
  - No significant influence on protons
- **Ramp**
  - Cause about 10% anti-proton losses
    Anti-proton emittance growth during the ramp may be beam-beam related.
  - Not much influence on protons
- **Squeeze**
  - Anti-proton losses are low
  - Proton losses are occasionally vey high - causing quenches.
- **Collision**
  - Anti-proton and proton lifetimes not much affected by beam-beam at present intensities in good stores.
  - Occasionally have large emittance growth of anti-protons at start of store.
  - Proton losses (thought to beam-beam related) can sometimes be higher than acceptable

Improvements

- Increasing the beam separations at all stages.
- Improving the alignment in the Tevatron.
- Smaller beam emittances.
- Operating with lower chromaticities (together with octupoles).
- Improved IR optics, e.g. local decoupling.
- Different bunch patterns.
- Active compensation of beam-beam effects

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